**FINAL REPORT SUBMITTED TO THE OFFICE OF NAVAL RESEARCH**

**Title:** Tactical Alteration of Blade Tonals in Underwater Vehicles Using Active Control of Biomimetic Muscles

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## 1. Introduction

The goal of this project is to achieve stealth by altering blade tonals, which occur due to the operation of a propulsor in a nonuniform flow, using active control of biomimetic muscles. Stealth is accomplished by many biological organisms through the introduction of suitable unsteady hydrodynamics. By modulating additional surfaces, these organisms appear to affect lift, drag, and related wake producing features, a combination of which may lead to a modification of the underlying acoustic characteristics. The question is whether the distillation of these features and their incorporation in an underwater propulsor for the purpose of noise reduction is a feasible endeavor. In this project, to achieve stealth, active control will be used, which consists of intentional articulation of suitable surfaces or boundary conditions in the vehicle using external energy.

One of the main sources of noise production is direct radiation. Radiated noise is due to several sources, which include (i) fluctuating volumes, (ii) fluctuating forces, and (iii) turbulence. Fluctuating thrust and side forces are produced due to the operation of a propulsor in a non-uniform wake. In particular, a wake deficit is produced due to the presence of a stator or a guide-vane in a uniform flow [1,2]. When this wake deficit is incident on the rotor blade, it generates an unsteady force, resulting in noise. Each rotor blade-geometry results in a specific spectrum of noise, and therefore generates a specific "signature" of the radiated noise.

Active control is the procedure of external modulation of relevant parameters of a process in an attempt to improve its performance. In the context of flow control, this procedure concerns the articulation of suitable boundary conditions of the flow-field in order to generate improved performance. Active control has been used in attempts to improve various performance metrics including lift effectiveness, reduction of various tones, drag reduction, flow separation control, and maneuverability [3]. In this project, we will use active control to modify radiated noise characteristics in underwater propulsors. In particular, a control surface (for example, biomimetic blades attached to the propulsor) will be appropriately modified so that the "acoustic signature" is modified or altered to resemble a different "blade signature". For example, it is known that skewed blades and radial blades produce quite different signatures. The question that could be posed in this case is if radial blades combined with an active control strategy appropriately synthesized can produce signatures that mimic another blade geometry (for example, skewed blades). It is to be noted that the goal here is to alter the noise characteristics rather than suppress the noise, at a given location. This unique approach opens up several new possibilities of actuation since it may place smaller demands on the active controller, both in terms of amplitude reduction, and in terms of the number of degrees of freedom that the actuation introduces.

The method of actuation that was used in this project is the use of "artificial muscles" attached at the trailing edge of the stator propulsor blade. It has been observed that the noise spectrum is affected by modulating such active combs [4]. These combs appear to have the ability to destroy large structures in the shear layer by seeding the flow with new patterns. Modeling the effect of these muscles/combs as a circulation input at the trailing edge, preliminary studies have shown that the circulation has a significant impact on the radiated noise characteristics [5]. The artificial muscle include customized biomaterials composed of shape-changing conducting polymers, which will be commanded by active-adaptive control strategies so as to achieve noise reduction.

## 2. Approach

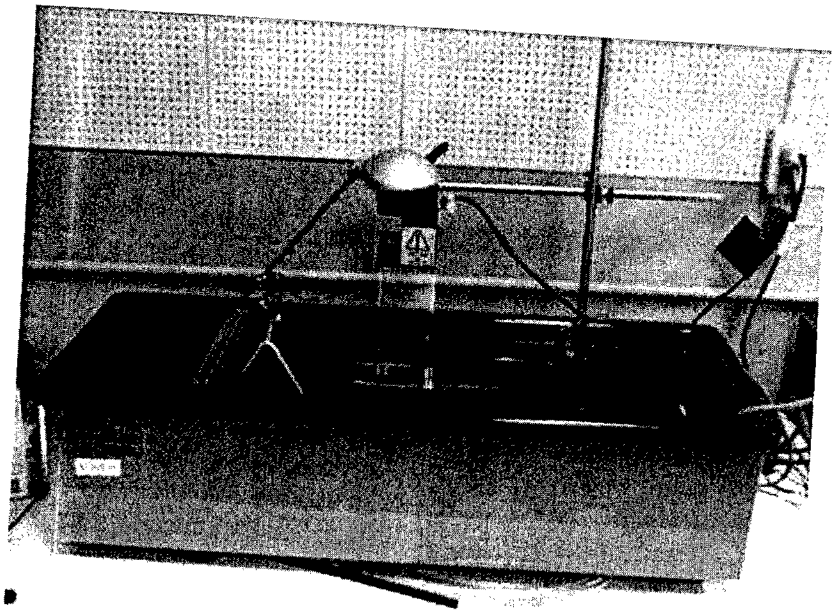


Figure 1: The Armfield open-channel water-tunnel

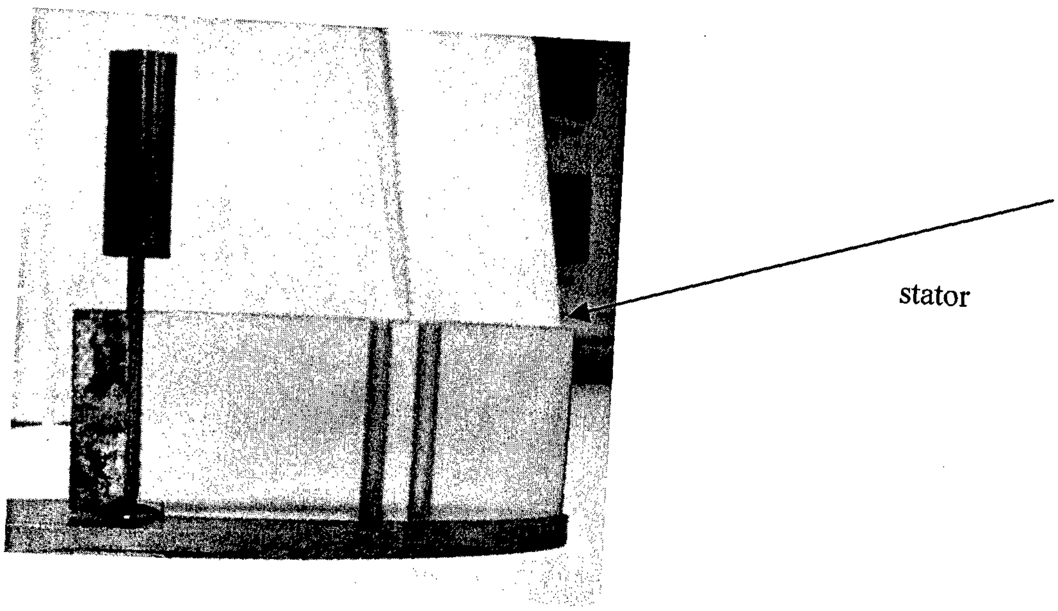



Figure 2: The stator with a "tail"

Our first step was to instrument a benchtop experiment where the proposed concept of tail-articulation can be validated. During 2001-2002, an Armfield hydrogen-bubble flow visualization water-tank was purchased and installed (See Figure 1). The tank has an entrainment jet circulation system and a flow straightener to achieve laminar or turbulent flow around test specimens on the order of 2-4 inches long. A lighting system and hydrogen bubbles can be used to visualize the flow in the tank. A symmetric hydrofoil of about 100 mm chord and 12% thickness (NACA 0012 series) was fabricated in-house out of plexiglass (figure 2). A matching tail-section of 10mm chord capable of span-wise oscillations was also fabricated. Various mounting fixtures were built to facilitate measurements and actuation. A TSI hot-film anemometer system was set up for making velocity measurements.

The goal of this proposal is to achieve stealth through the reduction or alteration of radiated noise that produce blade tonals in underwater vehicles using active control. The idea is to achieve the reduction through an intentional articulation of suitable surfaces or boundary conditions in the vehicle using external actuation and the above experimental setup. In particular, two different actuation systems were used to move the "tail", (i) a conducting-polymer based tail articulation, and (b) a stepper-motor based tail articulation. The progress accomplished in both items (a) and (b) is documented below:

## 2.1 Actuation Methods

Encapsulated Conducting Polymers (CP):
The active material in the CP based actuator design is polypyrrole, a conducting polymer [10]. These organic polymer molecules contract when a potential is applied and ions from a surrounding electrolyte diffuse into the polymer. The polypyrrole is fabricated in thin films. When activated these films contract uniformly in all in plane directions, producing strains of approximately 2%. To provide a mechanical amplification of the small strains and strain rates to yield useable motion for the purpose of this experiment, a bilayer is used. Tow polymer films 20 microns thick are laminated together with a spacer in between to form a bilayer. This way small motion of the films relative to each other causes a bending of the bilayer and a large amplification of the motion of the polymer films. However, this motion amplification causes a proportional loss of force generated. Fabrication of a useable bilayer actuator involves four steps:

1. Polypyrrole films must be synthesized to provide the raw material for the bilayer.
2. The polymer films are then assembled in layers to form a bilayer capable of actuation.
3. The actuator is then mechanically constrained to curl in a manner appropriate for this application. This is done using mechanical stiffening strips along the direction normal to the desired curl direction to constrain the motion as shown in Figure 5.

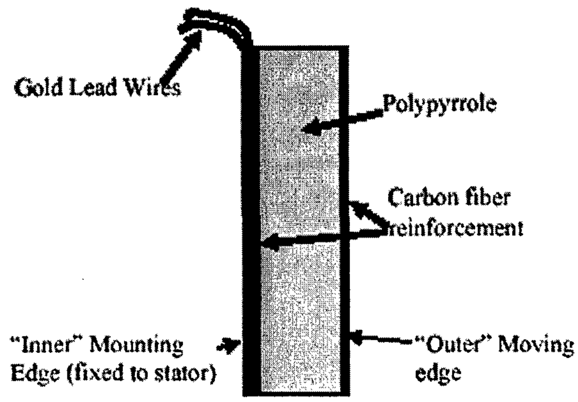



Figure 3: CP Design: Stiffening strips constrain curl to only one direction.

Another method used to constrain the curl involved cutting slits along the narrow dimension of the bilayer. This relieves the stress along the long dimension of the bilayer and causes it to curl only across its narrow dimension. This method gives a little bit reduced performance as compared to the stiffening strips method above.

4. The final step is encapsulation in plastic to allow operation in water and prevent the loss of electrolyte.

Stepper Motor:

Due to the bandwidth limitations of the CP actuators, another actuation method based on a stepper motor was also used in order to study the flow characteristics. A stepper motor was used because of its simplicity and large available bandwidth. The motor used was an "Mdrive 17" manufactured by Intelligent Motion Systems, Inc. It is mounted above the waterline directly over the pivot point of the tail. A drive shaft attached to an aluminum "tail" section is directly attached to the motor output shaft (see Figure 4). This drive shaft sits at the trailing edge of the stator model and serves as the hinge and transition between the stator section and the articulated tail section. By design, this drive shaft is wide as the stator thickness where it is mounted, 90% of the chord length from the leading edge of stator. This leaves the articulated surface as 10% of the chord length of the stator.

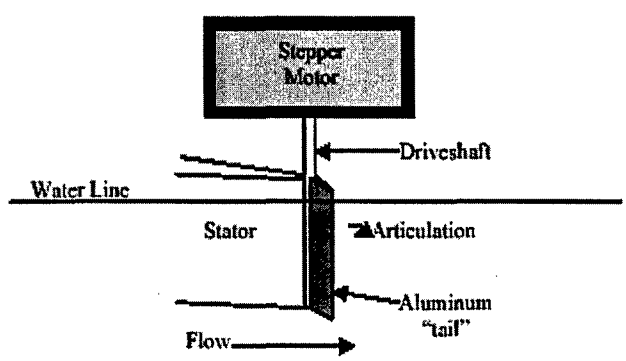
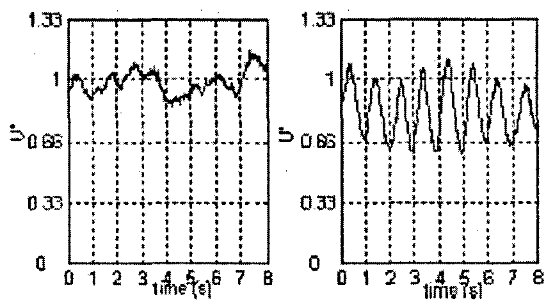



Figure 4: Tail articulation using the stepper motor.

### 3. Results

1. **CP-based tail articulation:** A polypyrrole-based conductive polymer was grown[1] in thin-film form, two of which are then assembled in layers to form a bilayer capable of actuation. The actuator is then mechanically constrained to curl maximally in the transverse direction and minimally in the longitudinal direction. This bi-layer actuator is encapsulated in a suitable plastic cover to allow operation in water. The resulting actuator was attached to the stator to serve as a biomimetic tail, and immersed in the open-channel water tunnel described above. Figure 2 shows the impact of the tail articulation using the current CP actuator. It can be seen that the actuator has a significant impact on the flow velocity.




(a) (b)

Figure 5: Flow alteration due to bilayer oscillations. (a) Without articulation and (b) with CP articulation at 1 Hz.

The following properties summarize the observations with this CP-based tail [6,7]:

a. Tail tip speed is an important parameter concerning wake deficit alteration.

b. There is an upper limit to the frequency of effective desirable wake alteration.

c. A 10-degree peak-to-peak deflection at 0.1 Hz was achieved using the conducting polymers, at a tank flow-speed of 4 m/s. As the tail-speed is increased, the achievable tail deflection is reduced.

d. The velocimetry measurements indicated that a 30% perturbation in the flow velocity can be achieved downstream due to the tail-articulation. This represents the best performance achievable using the currently available polypyrrole CPs.

2. **Stepper motor-based tail articulation:** A stepper-motor based tail articulation was also carried out in order to determine the optimal noise reduction achievable using the concept of tail articulation. A stepper motor was used because of its simplicity and large available bandwidth, with the help of which we can determine the optimal actuation required to achieve the maximal wake deficit reduction. Motor was mounted above the waterline directly over the pivot point of the tail. The drive shaft of the motor was attached directly to an aluminum tail. Different actuation frequencies and waveforms were tried and the velocity of the flow was measured at

[1] In collaboration with Dr. Hunter's Bioinstrumentation Laboratory

80% of the stator-chord length (8 cm) downstream along the whole width of the water tunnel. This way the effect of tail articulation on the flow field and wake was measured accurately as a function of time. An example measurement is shown in Figure 6 without any actuation, and with actuation in Figure 7. The amplitude and frequency of this tail motion were chosen so that they result in the optimal drop in wake deficit. It can be seen that this results in a "gap" in the wake as it becomes partially discontinuous at 15-16 seconds. This drop could be exploited especially well if the blade were to be timed properly and pass through this gap. It was found that the wake deficit is reduced most effectively for Strouhal numbers between 0.25 and 0.35 and this is the theoretical optimal range previously predicted and observed by others for propulsion efficiency in fish.

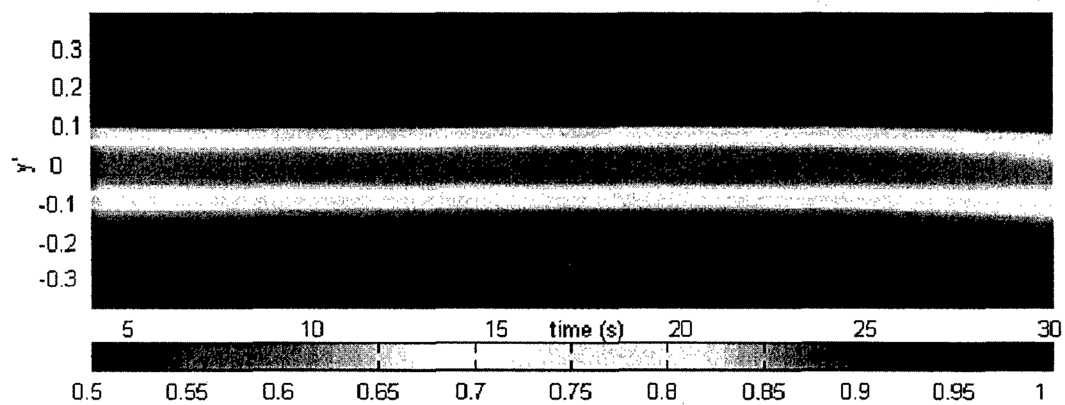



Figure 6: Baseline streamwise velocity U' (=U/Free stream speed) at 80% of chord length downstream of a stator with no trailing edge articulation, shown as a function of y' (=y/Stator Chord Length) and time.

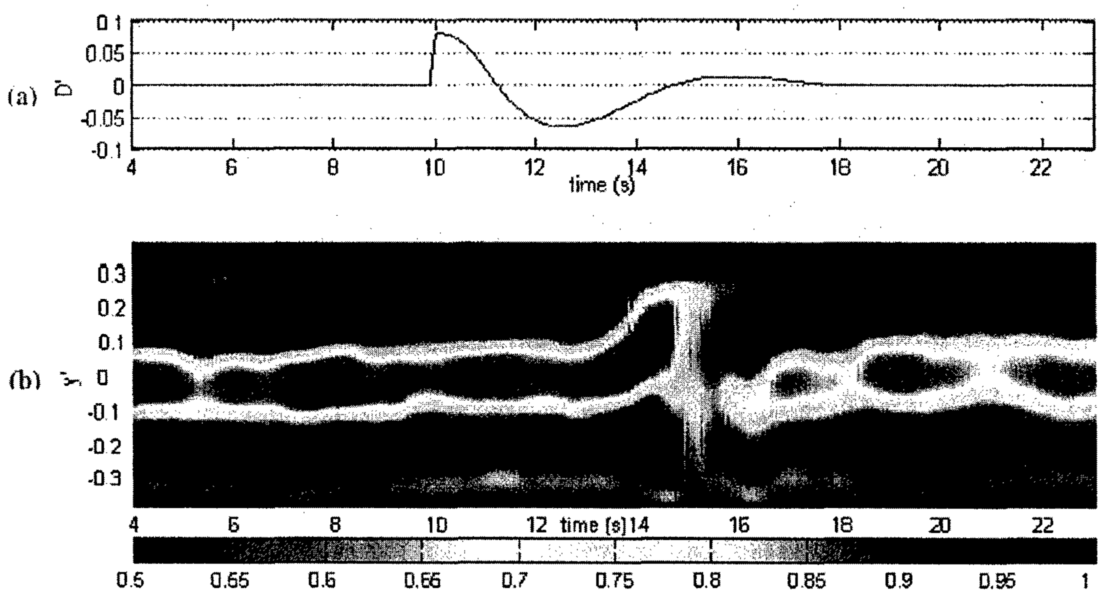



Figure 7: Flow field with designed move profile showing (a) tail tip displacement D' (=Tail deflection/Stator Chord Length) (b) U' (=U/Free stream speed).

Following key observations were made with the help of these experiments [6,8]:

e. A gap having very little wake deficit can be produced over an interval of time that can be exploited especially well in the blade were to be timed properly and pass through this gap.

f. Optimal Strouhal numbers for wake deficit reduction were found to be in the range of 0.25 and 0.35. Thus the results from this experiment show that the operating regime for the optimal wake deficit reduction is similar to that for propulsion efficiency, with an almost identical optimal range of Strouhal numbers.

g. Wake deficit can be reduced by up to 60% using stepper motor based tail articulation.

**Impact on Noise Reduction:** Noise generation was predicted by passing a numerically simulated rotor blade through the measured flow field. Simulations show that sound pressure level at dominant frequency is reduced by 2-10 dB by using a constant sinusoidal tail motion and by 2-25 dB using a transient tail motion [6,8].

## A Comparison of CP-based and Stepper Motor-based Tail articulation

Proof of concept demonstrations of noise reduction was achieved in the experimental test-bed using CP-based and stepper motor-based tail articulation. Both of these demonstrations were achieved at a Reynolds number of 4000. Specifically it was shown that by using transient tail motion of the stator, the wake deficit can be reduced by more than 60% corresponding to the radiated noise reduction by 2-25 dB at dominant frequencies. The current CP actuator design achieves approximately 40% of the required deflection for the desired wake reduction based on stepper-motor based tail articulation (see Figure 4).

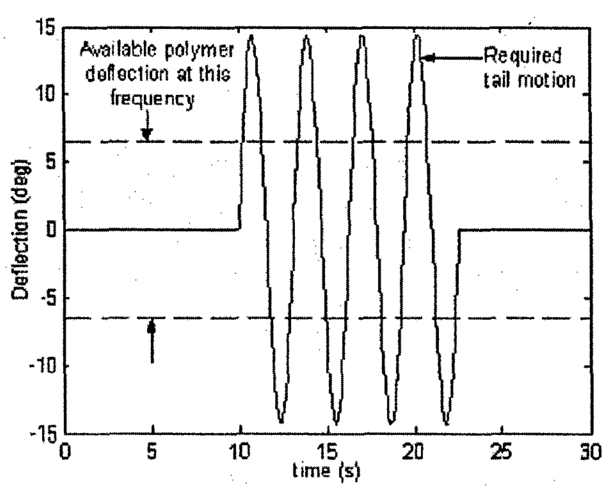
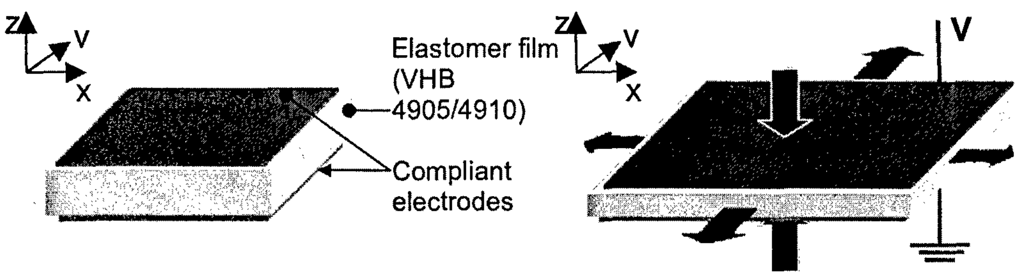



Figure 8: Minimum required motion for wake deficit reduction and available CP actuator deflection.

A different set of polymers that have very little self-noise production was also explored for tail articulation. These polymers are briefly described below.

### Dielectric Elastomer Actuators[2]

Dielectric elastomer actuators have great potential as robotic actuators because they overcome most of the inherent limitations of current actuators such as DC motors and pneumatic/hydraulic cylinders while being simple and low cost [11,12,13]. Unlike traditional actuators that produce motion by having rigid parts in relative motion with each other, Dielectric Elastomer actuators produce motion by deforming some of their parts. Typically, Dielectric Elastomer actuators consist of an elastomeric film coated on both sides with compliant electrodes, as shown on Figure 9a). Motion is caused by the compressive Maxwell pressure that occurs when an electric field is applied across the film by applying a high voltage differential between the two compliant electrodes, again shown on Figure 9b). It has been shown by SRI that the equivalent pressure acting on the film surface is given by the simple relation $P = \varepsilon\varepsilon_0 E^2$ ; where ε is the free space permittivity, $\varepsilon_0$ is the material dielectric constant and E is the electric field. Since the film is thin relative to its width, ≈ 0.1 mm vs 100 mm, it cannot support planar compressive forces as it expands and should therefore be kept under tensile loading at all times to avoid buckling.




a) Actuator in its undeformed state

b) Application of a high voltage causes the film to compress in thickness and expand in area

**Figure 9: Dielectric elastomer actuator operating principle [4].**

If the film is incorporated into a compliant frame with appropriate preloading, as shown in Figure 10, the film's orthogonal expansion can be converted into useful mechanical work. Linear strains of approximately 200% are possible with such a design [14]. When compared to conventional DC motor/gearhead combinations, dielectric elastomer actuators contain 10 to 100 times fewer parts. Since they can be all plastic, they are also much lighter than conventional actuators. Finally, since an EPAM's motion involves

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Field and Space Robotics Laboratory, MIT material deformation rather than sliding and rolling mechanical surfaces, close tolerances and lubrication are not required for good performance and durability.

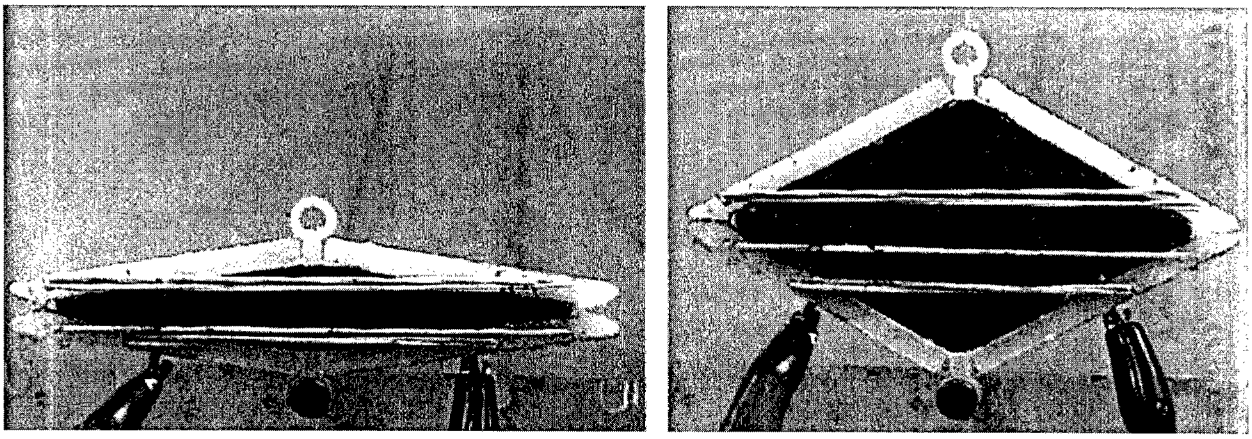

**Figure 10: Experimental dielectric elastomer actuator showing 200 percent strain.**

Dielectric Elastomers have been studied since 1995 and most of the published research over the last several years has been exploratory. In this period, many different Dielectric Elastomer actuator concepts were implemented into simple robotic applications [11]. Very promising performance numbers have been reported by various researchers:

- actuators with useful strains of 200% and 10:1 force to weight ratio have been demonstrated;
- electromechanical efficiencies of about 60-90% and bulk material energy densities of 3-4 J/g were reported [11].

Proof-of-concept calculations, using added mass analysis show that EPAM actuators are more than capable of driving stator tail articulation. For example, a stator with a chord length of 3 in and a 1 in tail flapping at 5 Hz with amplitude of 2 degrees in a 1m/s flow field would require approximately 0.24 in-lbs (0.027 Nm) of torque. This translates to a 0.039 lb (0.173 N) force requirement if acted upon a 6 in (152.4 mm) lever arm. EPAM actuators have already been produced that are capable of generating 0.11 lbs (0.489 N) of force. Figure 5 shows schematics of several possible EPAM articulation concepts using both rotary and linear actuators.

While EPAMs are not the only proven polymer actuation technology they are the most viable for use in underwater vehicle noise reduction. Conducting polymers (CP) are another maturing technology however these actuators have neither the frequency response nor ultimate force generation capabilities that EPAMs do. Additionally, CP actuators must be waterproof encapsulated in order to function submerged. Encapsulation proves to be difficult with CPs which ultimately makes them impractical for use in underwater vehicles. CPs must be grown, a process that is currently difficult to control and unreliable.

The operating characteristics of these actuators, specifically their low noise, low power-requirements and high material energy densities, make them ideally suited for use in this application. Research focused in this area would significantly accelerate the process of producing a viable tail articulation system for use in unmanned underwater vehicles.

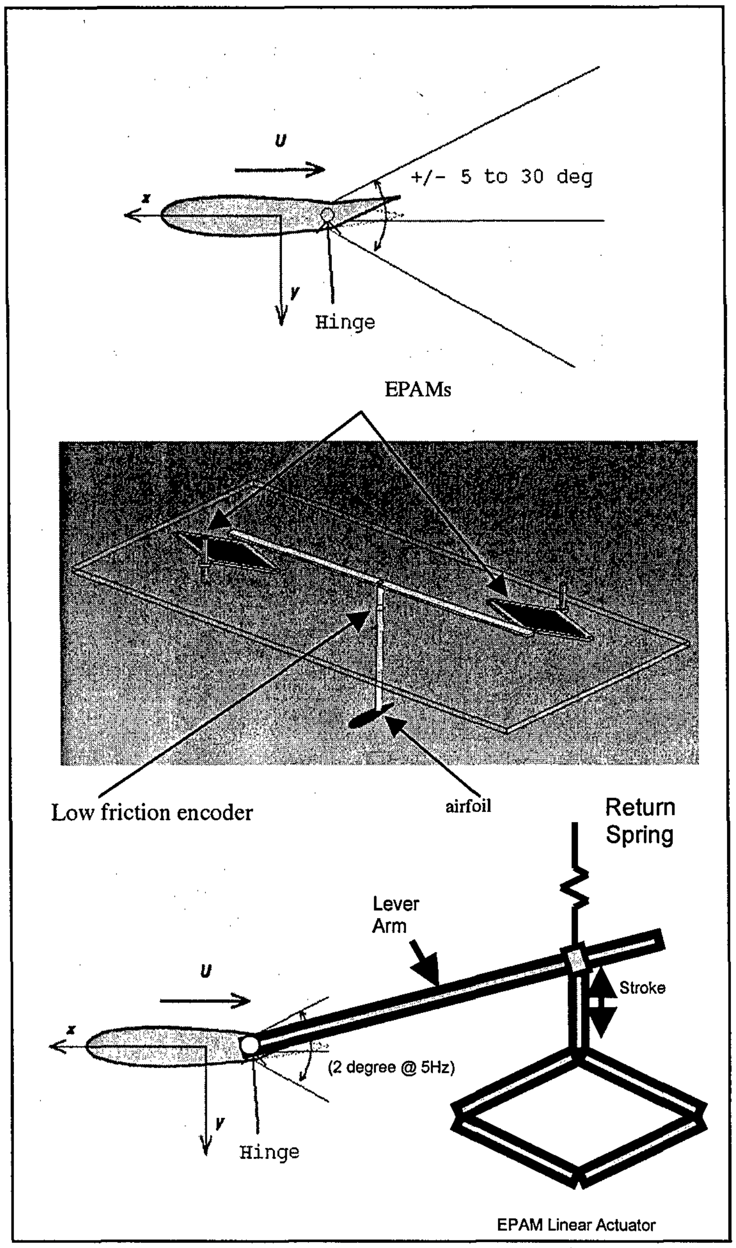


Figure 6: Tail articulation using a rotary dielectric elastomer

## Impact/applications

The main application of this technology is in the design of marine propulsors with an articulated tail so that the surrounding flowfield is continually altered and controlled to some extent. A successful implementation of active control of blade tonals will have direct implications on stealth properties of underwater propulsors, since the net result of the proposed effort will be an alteration, or perhaps even reduction of the blade tonals that are produced due to unsteadiness in the flow-field. Even a few seconds of delay in detection can result in paramount savings for the US Navy.

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